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TECHNICAL NOTE

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AN INVESTIGATION OF A PHOTOGRAPHIC TECHNIQUE OF MEASURING HIGH SURFACE TEMPERATURES

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AN INVESTIGATION OF A PHOTOGRAPHIC TECHNIQUE OF MEASURING HIGH SURFACE TEMPERATURES

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SUMMARY

A photographic method of temperature determination has been developed to measure elevated temperatures of surfaces. The technique presented herein minimizes calibration procedures and permits wide variation in emulsion developing techniques. The present work indicates that the lower limit of applicability is approximately 1,400° F when conventional cameras, emulsions, and moderate exposures are used. The upper limit is determined by the calibration technique and the accuracy required.

INTRODUCTION

Recent studies conducted in conjunction with the aerodynamic heating problem have demanded a temperature-measuring technique capable of measuring surface temperatures and determining temperature contour maps of heated surfaces.

A survey of available temperature-measuring devices has not revealed any method that would be completely satisfactory.

Preliminary studies indicated that a photographic technique would be the most promising method since a photographic emulsion will detect differences in the surface brightness of a material at elevated temperatures. In addition, an emulsion provides a view of a large surface area at any given time. Since the photographic method produces a calibrated photograph of the heated surface, temperature contour maps can be made in detail. Also, such a photograph can be used to determine stagnation-point location. Furthermore, the photographic method is readily adaptable to almost any ground-testing facility and can be adapted to recoverable flight models.

The basic principle of the photographic method can be defined in the following manner. If a photographic emulsion is exposed to the visible radiation of some high-temperature incandescent source, the

resulting negative will be most dense in the regions of highest temperature and least dense in the regions of lowest temperature. The intermediate temperatures would be represented by intermediate densities. The response of the emulsion will be dependent upon the total energy and the spectral nature of the radiation. Previous photographic techniques depend upon the use of identical emulsion batches and delicate development procedures unless each unit of film contains a complete temperature calibration. This analysis presents an improved method of using a calibrated photographic emulsion to determine elevated temperatures of surfaces. Calibration curves are given for a temperature range of 1,400° F to 3,600° F.

SYMBOLS

E	relative exposure, $\frac{I_o}{I} t$ or $\epsilon \frac{t_e}{f^2}$, sec
f	lens aperture setting
I	transmitted light intensity, watts-meter^{-2}
I_o	incident light intensity, watts-meter^{-2}
T	temperature, °F, abs
t	time, sec
ϵ	surface emissivity
λ	wavelength, microns

Subscripts:

e	exposure
T	surface temperature

ANALYSIS

A study was first made of the relationship between film density, exposure, and body temperature to determine whether calibration curves might be predicted for a particular type of film. In order to make such a study, it was necessary to consider both the film properties and the properties of body radiation. As far as it is known, the

analysis that follows has not been previously exploited in photographic pyrometry to permit simplification of the film calibration procedure.

Energy Distribution of Body Radiation

Figure 1 illustrates the spectral distribution of radiation from a black body at several different temperatures (from ref. 1). The portion of the spectrum representing visible radiation is identified by the hatched area. The hatched area is also representative of the part of the spectrum to which the film is sensitive and shows the relative energy emitted by a black body in the film spectrum. The relative energy change with body temperature in the visible spectrum varies between T^{11} and T^{14} for black-body absolute temperatures below 3,000° F. The value of the exponent in the energy relation decreases with increasing body temperature. The large exponential value of temperature is attributed to the rapidly varying energy level with temperature in the visible spectrum (ref. 2), and this variance contributes greatly to the accuracy of the photographic technique.

Determination of Emulsion Response to Visible Body Radiation

The exposure constant of the photographic emulsion is essentially the integrated area under the spectral-sensitivity curve shown in figure 2 for Kodak Tri-X Pan Film. If the spectral sensitivity of the emulsion were uniform with wavelength, the response of the film to visible radiation would be the same as the energy change with wavelength in the visible spectrum. Unfortunately, the spectral sensitivity is not uniform, but varies with wavelength as shown in figure 2. In view of this fact, the calculation of the film response is weighted according to the variation of the film sensitivity with wavelength. At a given black-body temperature, the ratio of film sensitivity to energy intensity is taken at a number of different wavelengths between the spectral limits of the film. The summation of the ratios at a given black-body temperature determines the relative response of the film at the given temperature. Calculations of this type are made for several black-body temperatures in order to determine the relative exposure variation required to obtain a constant density on the film.

APPARATUS

Camera

The camera and some associated equipment used in this investigation to photograph the test specimen are shown in figure 3. The camera is a

modified K-24 aerial camera. A lens mount was constructed to employ four matched lenses; thus, four different exposures could be obtained on a single shutter action. The lens focal length is approximately 3.75 inches. The shutter is a focal-plane type consisting of a slotted curtain which passes over the film at a fixed rate. The exact exposure time for all lenses is determined with a photocell and oscilloscope. The lens aperture ranges from f:3.75 to f:22. Smaller effective apertures are obtained by placing additional calibrated diaphragms at the optical center of the lens and by placing neutral-density filters in front of the lens.

Radiation Source and Reference Black Body

Two different facilities were used to produce known elevated surface temperatures of high emissivity for the purpose of experimentally calibrating the film.

An Inconel plate $\frac{1}{16}$ inch by $1\frac{1}{2}$ inches by 9 inches was heated by its electrical resistance to produce temperatures up to 2,000° F. Initially, the strip was heated to 2,000° F for 15 minutes to obtain a stable oxide coating on the surface. The surface emissivity was approximately 0.7 to 0.8 (ref. 3). The actual surface temperature was measured by thermocouples. (See fig. 3.)

Induction heated furnaces were used as a source of black-body radiation. These furnaces have temperature capabilities of 2,400° F and 4,000° F. In order to reduce error in film calibration, any background lighting was eliminated. In other cases where background lighting could not be eliminated, photographs were made to determine the intensity.

Film Processing and Associated Equipment

The photographic film used in this investigation was processed in Kodak Microdol Developer. The developer was diluted with 1 quart of water to 1 gallon of developer, and the developing time extended 5 minutes. Development time was increased to lessen the chance of error. A universal hardening fixer was used as the acid fixing agent in accordance with the manufacturer's recommendations.

The film density was measured with a densitometer. In order to facilitate reading and handling of the film, the film images were magnified by projection approximately 8 to 10 diameters with a photographic enlarger to increase the area resolution.

Photographic Emulsion

Kodak Tri-X Pan Film was used because the basic characteristics of the film were suitable for use in this investigation. The speed of the film is relatively high and the spectral response covers the visible spectrum. A curve of the relative spectral response is shown in figure 2. A high-speed film was necessary since the surfaces to be photographed experienced a rapid temperature rise. An infrared film would be useful at the lower temperatures, but the lengthy exposures required by most infrared films could not be tolerated at the high temperatures of the present tests.

CALIBRATION

An important fundamental characteristic of an emulsion to be considered is the variation of relative optical density $\log_{10} \frac{I_o}{I}$ with relative exposure $\epsilon \frac{t_e}{f^2}$. If the emulsion is exposed to visible radiation of constant intensity and the resulting film densities are plotted as a function of exposure time, the data will define a flattened S-shaped curve (refs. 4 and 5). A curve of this type for Kodak Tri-X Pan Film is illustrated in figure 4. For all practical purposes, the portion of the curve between the approximate densities of 0.1 to 1.0 can be taken as a straight line. Only the linear portion of the curve is considered in this investigation.

A number of exposures were made of the heated Inconel strip and the black-body radiators at various known temperatures. The resulting film densities for each temperature were plotted as a function of the relative exposure E where

$$E = \epsilon \frac{t_e}{f^2}$$

Figure 5 is a typical example of the type of results obtained. The series of constant-temperature curves are essentially the basic characteristic curves of the emulsion for a series of different light intensities. If the development is constant for all exposures, the curves will have the same slope. Such conditions were rigidly controlled for these tests. The hatched area on the curve for a temperature of $1,800^{\circ}$ F indicates the maximum scatter experienced in the data.

Approximately 15 sets of curves, such as the one shown in figure 5, were used to establish a well-defined curve showing exposure variation with temperature for constant film density. The variation is presented in figure 6. For the purpose of presenting the data, the relative film exposure values for each intensity level or surface temperature have been based on the relative exposure value at 1,400° F and shown as a ratio. The experimental data lie within the hatched area which indicates the maximum scatter of the test points. The variation of exposure with temperature shown in figure 6 is essentially the spacing between the constant-temperature calibration curves in figure 5 at constant film density. The data agree well with the solid-line curve calculated by the method of the analysis and also with the points calculated for the relative black-body energy change. The slight deviation at the higher temperatures is possibly due to smoke visible above 3,000° F in the black-body furnace. Therefore, since the spacing of the constant-temperature lines of figure 5 is mainly dependent upon the type of film used and the temperature of the surface photographed, the complete calibration over the entire temperature range can be determined on the basis of a few exposures of the temperature reference. A correction to account for surface emissivity values appreciably different from the emissivity of the calibration temperature reference might be required in some cases. The effect of uncertainty in emissivity values is further discussed in a subsequent section on errors.

SURFACE-TEMPERATURE MEASUREMENTS OF A 30° WEDGE-SHAPED MODEL

A practical application of the photographic temperature-measuring technique is presented in figures 7, 8, and 9. Figure 7 is a photograph of the 30° wedge-shaped model with a stably oxidized surface. The surface contains a spherical bulge that might represent a surface configuration for a high-speed missile. The model was tested in a hot air jet at a Mach number of 4 and a stagnation temperature of 2,600° F to determine the effects of the bulge on local aerodynamic heating. A typical photograph of the hot model is shown in figure 8. This photograph was taken approximately 6 seconds after start of the test. The white area in the center of the model indicates high temperatures on the spherical bulge. The photograph shows high contrast. However, the original negative used to make the temperature measurements showed much softer contrast and permitted a detailed temperature map to be made of the surface. A contour plot of this type is shown in figure 9. The localized heating is possibly due to shock impingement of the hot air jet.

A tungsten-filament standard lamp of known temperature and emissivity was used as a temperature reference to calibrate the film. Also, a photograph was made of a constant-intensity neon lamp simultaneously with each photograph of the model of unknown intensity. This procedure would indicate any exposure changes in the camera shutter.

The air from the hot jet did not have sufficient energy in the visible spectrum to have any effect on the emulsion. The low reflectivity of the model surface prevented any appreciable reflection of the jet hot bed. Thus, no base density occurred on the emulsion for a cold model.

Several thermocouples were attached to the back surface of the spherical bulge. Figure 10 shows a comparison of the surface temperature as determined by a thermocouple with that as determined by the photographic technique. This comparison shows that the agreement between the measurements by these two methods is very good.

ERRORS AND SENSITIVITY

Certain conditions causing error in the temperature measurement should be considered. The error induced by uncertainties in surface emissivity is in the same order of magnitude as that experienced with the optical pyrometer. The effect of this error is reduced because of the large intensity change of radiation with temperature in the film spectrum. For example, an uncertainty of 25 percent in surface emissivity corresponds to an error of about $\pm 35^\circ$ F at $1,600^\circ$ F and about $\pm 110^\circ$ F at $3,000^\circ$ F.

The nonuniformity in the spectral sensitivity of the emulsion was found to have little effect on the slope of the exposure-variation curve (fig. 6). This fact is due to the rapid intensity change in radiation for a small temperature change as compared with a maximum variation that might occur in the spectral sensitivity of a common emulsion. A calculation was made of the exposure-ratio curve by assuming that the spectral sensitivity of the emulsion was changed by a factor of 2. This change amounted to only about $\pm 75^\circ$ F at $3,000^\circ$ F. Variations in the spectral sensitivity with different emulsion batches would not normally be this great.

The sensitivity of the calibration system would be affected by the slope of the exposure-ratio curve. Since the slope of the exposure-ratio curve is dependent upon the spectral nature of the radiation (other factors being constant), controlled changes in the incoming radiation could produce a desired effect.

A series of calculations were made of the exposure response with the assumption that the radiation would be filtered so as to transmit only monochromatic light. Wavelengths of 0.44 micron and 0.65 micron were selected, and the resultant data are given in figure 11. If only the shorter wavelengths are allowed to fall on the film, the slope of the exposure-ratio curve is increased. Thus, the accuracy of determining the higher temperatures would be increased by use of filters passing monochromatic radiation at wavelengths of 0.44 micron. The

curve for $\lambda = 0.65$ micron indicates that transmission of the long wavelengths decreases the slope of the exposure-ratio curve.

CONCLUDING REMARKS

A simplified method has been investigated for measuring temperatures as a variation of density on a photographic emulsion.

The exposure-temperature curves for Kodak Tri-X Pan Film as determined from theoretical analysis and experiment show good agreement. Also, the relative energy change of black-body radiation with temperature shows a close correlation with the exposure change of the emulsion with temperature. From the study, it is concluded that a complete temperature calibration could be determined for essentially any type of film, based on a few film exposures to a temperature reference.

There is very good agreement between the surface temperature measurements obtained by the photographic technique and those obtained by the use of several thermocouples.

The accuracy at higher temperatures can be improved by use of filters passing monochromatic radiation at wavelengths of 0.44 micron.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 18, 1960.

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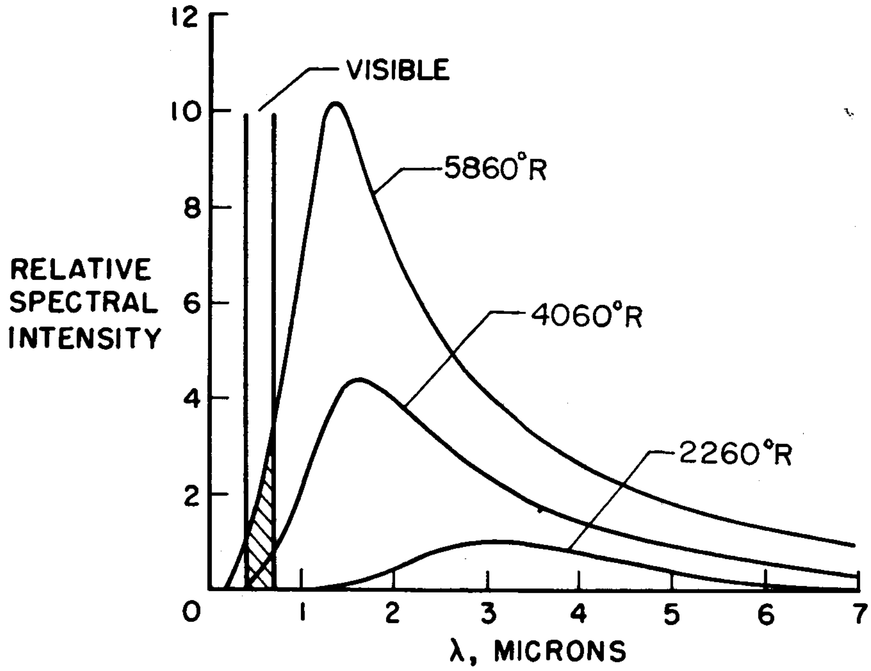

Figure 1.- Spectral distribution of black-body radiation (from ref. 1).

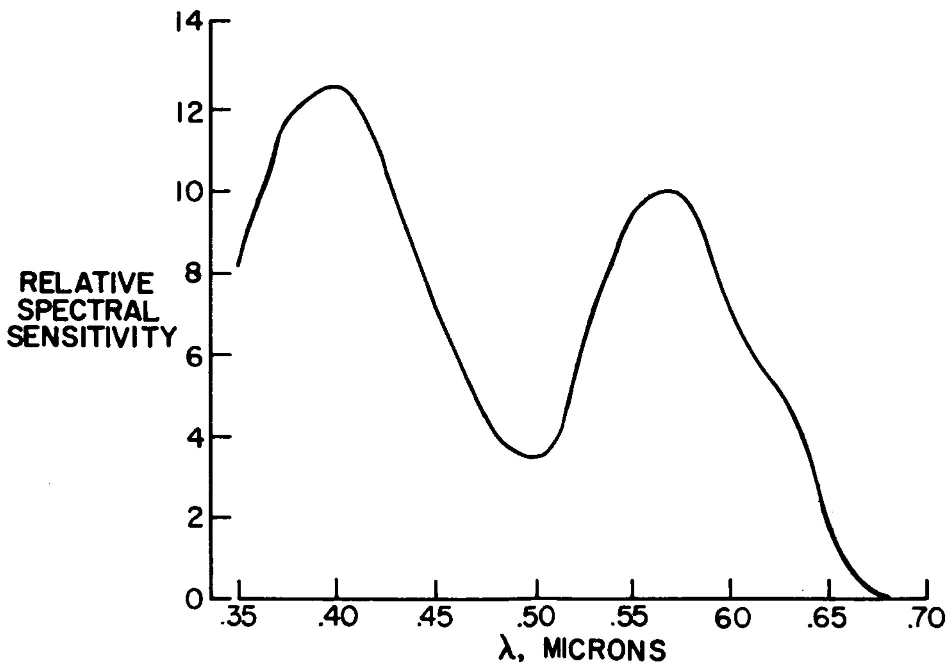

Figure 2.- Spectral sensitivity of Kodak Tri-X Pan Film.

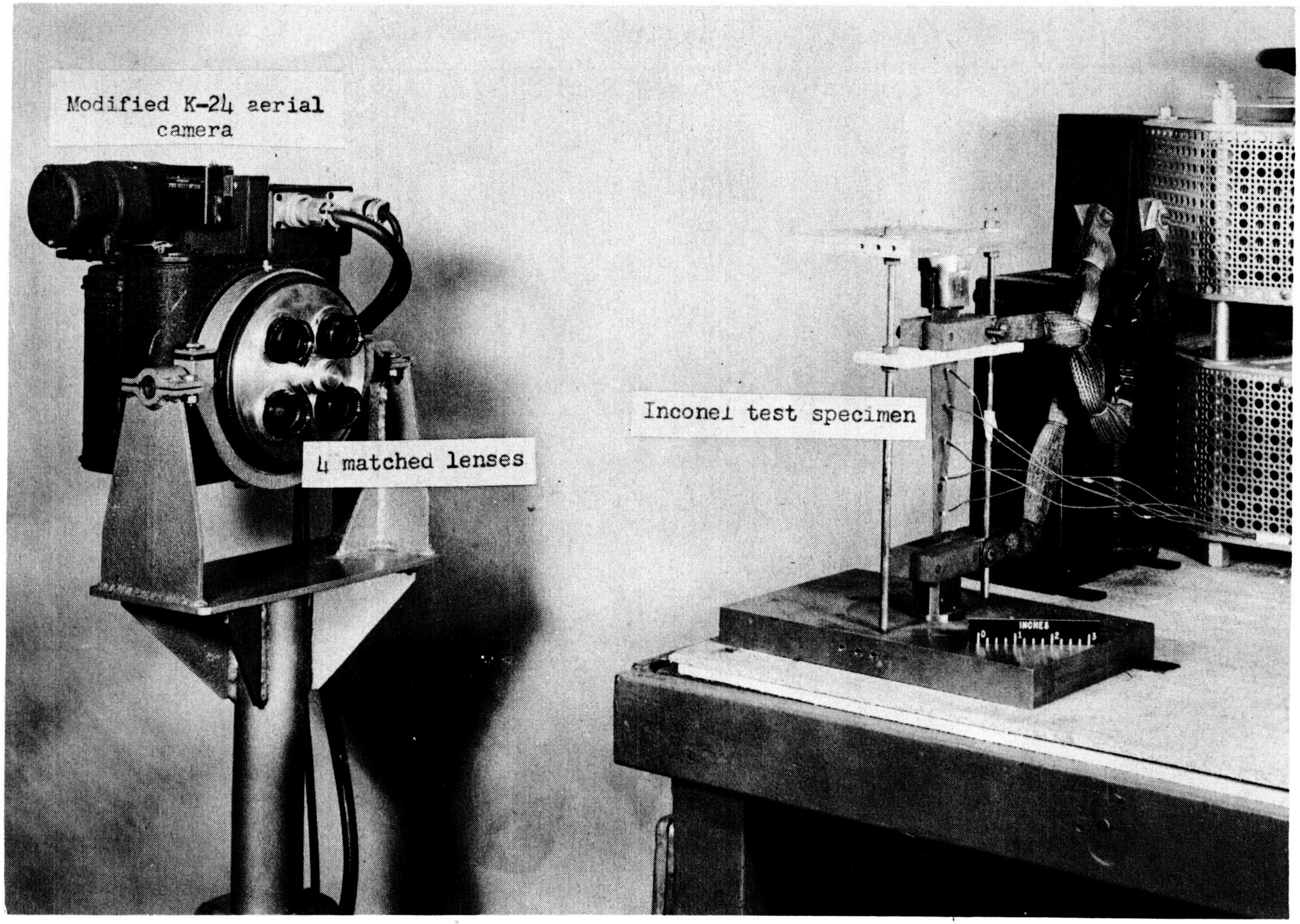

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Figure 3.- Test arrangement showing modified K-24 aerial camera and Inconel specimen.

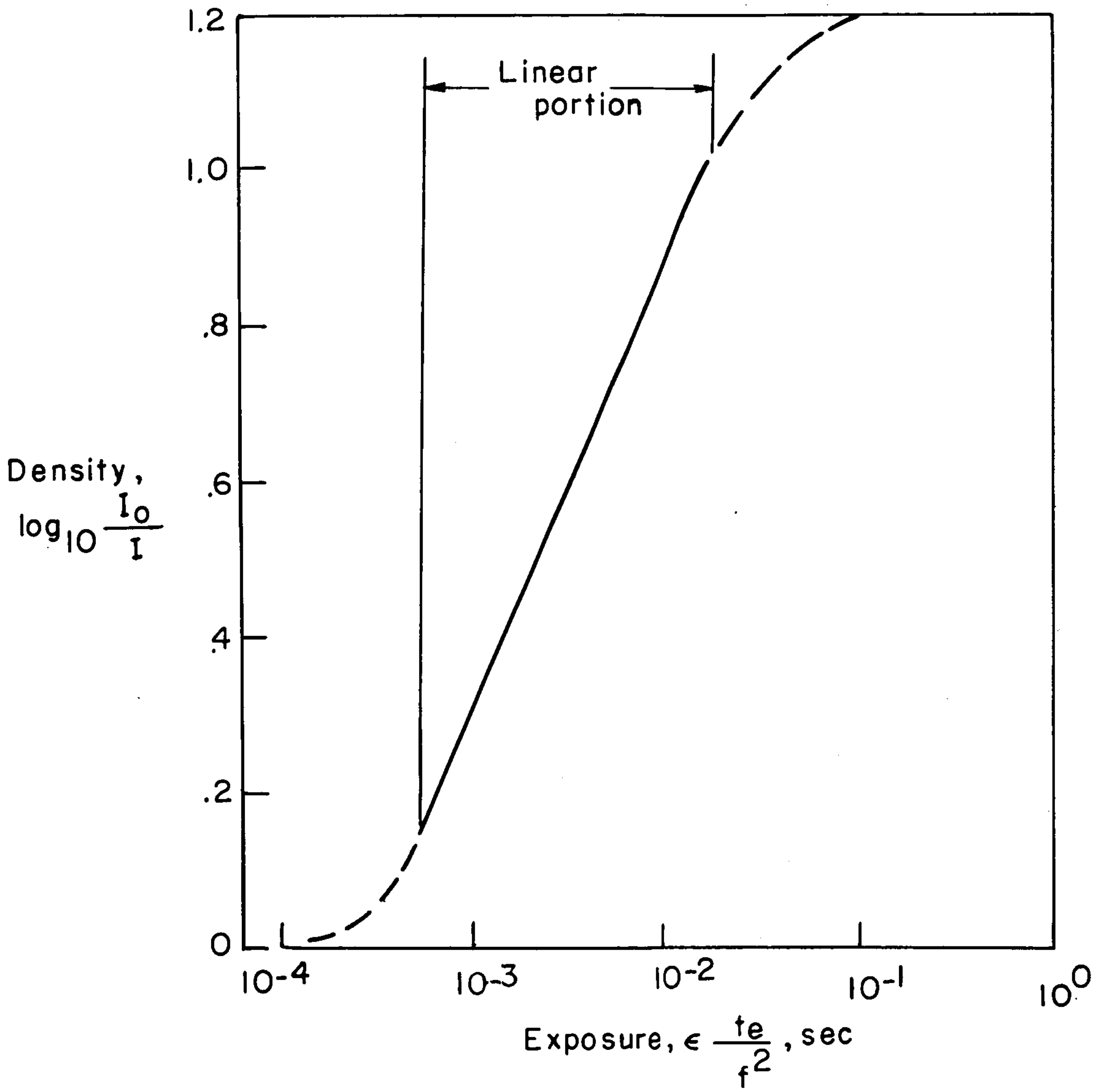

Figure 4.- Typical characteristic curve for Kodak Tri-X Pan Film.

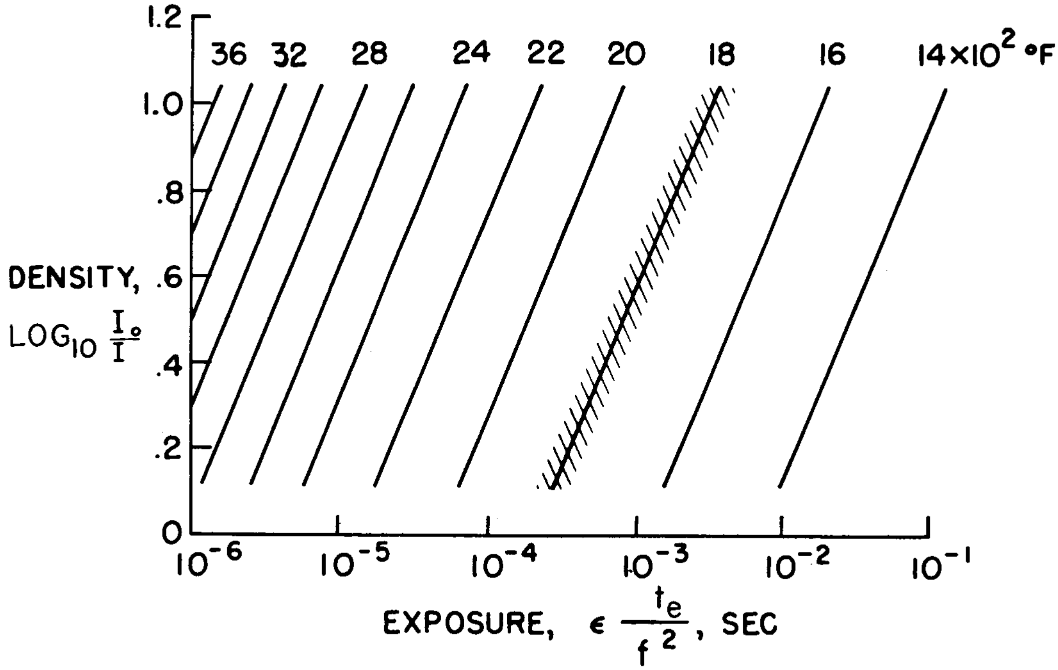

Figure 5.- Effect of temperature upon film calibration (Kodak Tri-X Pan Film).

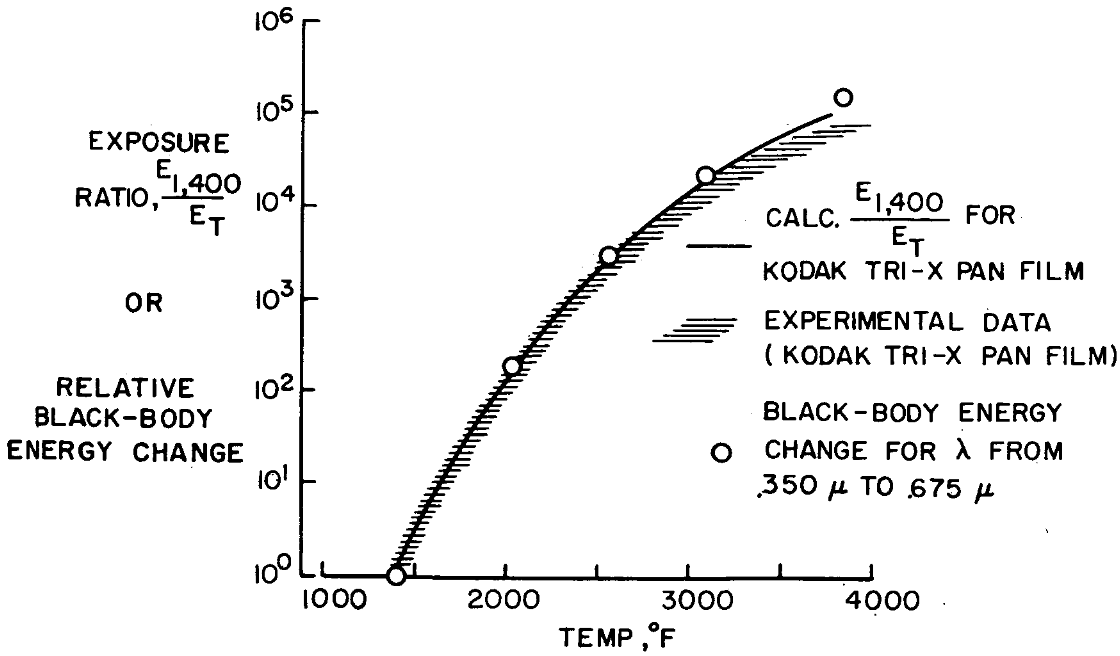

Figure 6.- Exposure ratio required for constant film density and relative energy change for black body.

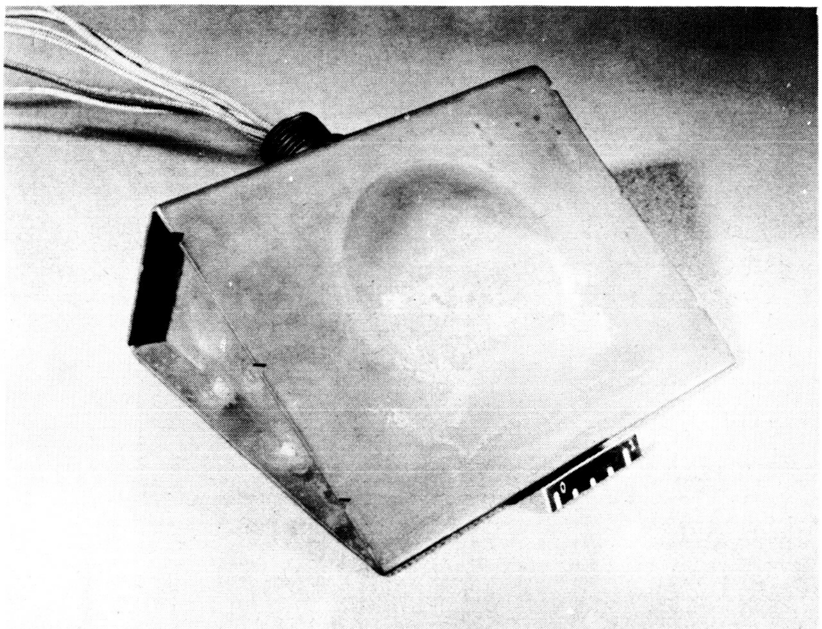

Figure 7.- Wedge-shaped model. L-57-4361

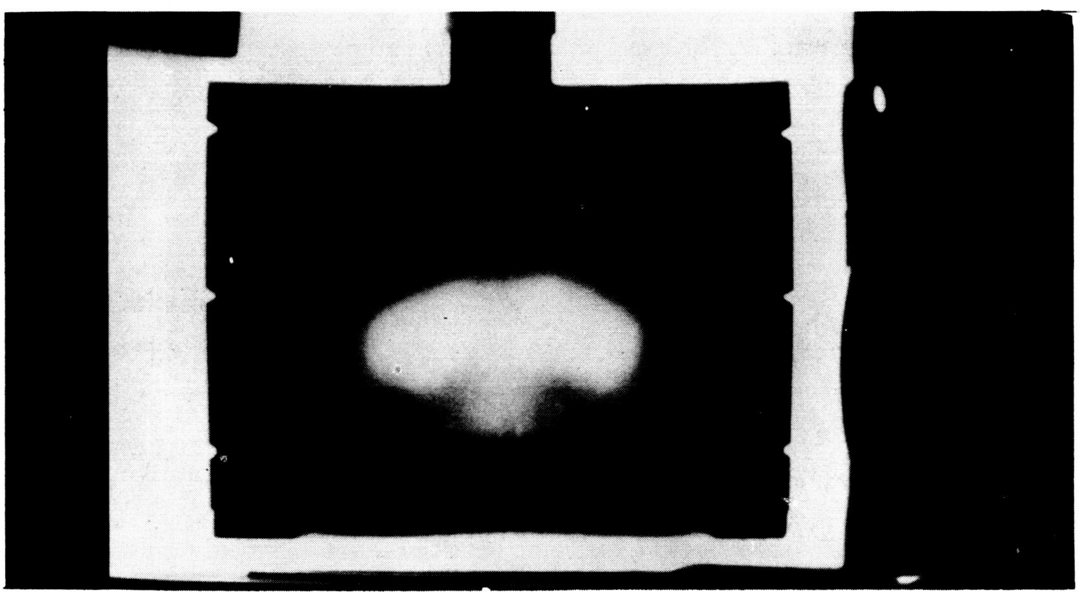

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Figure 8.- Photograph of wedge-shaped model taken with modified K-24 aerial camera.

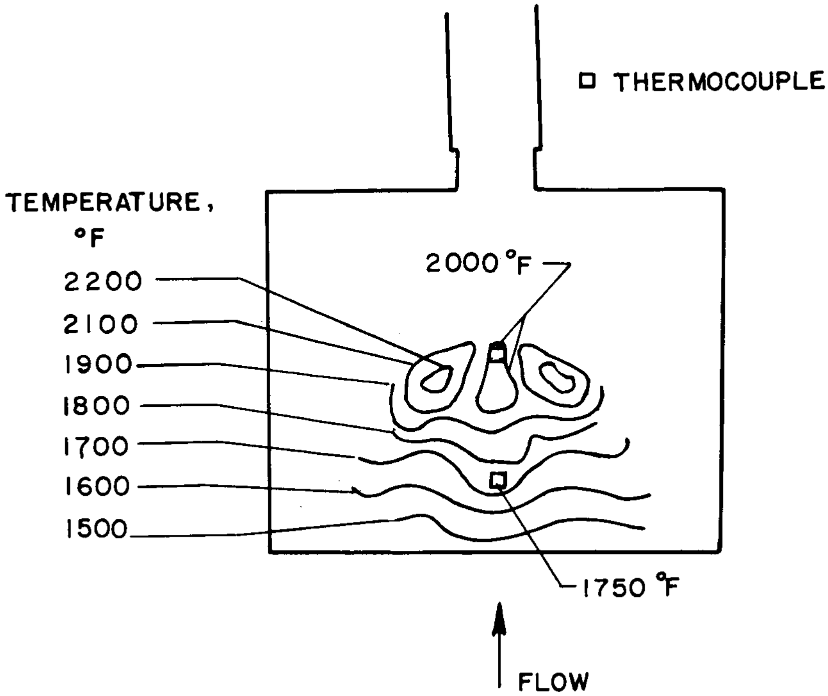

Figure 9.- Temperature contour plot of 30° wedge-shaped model.

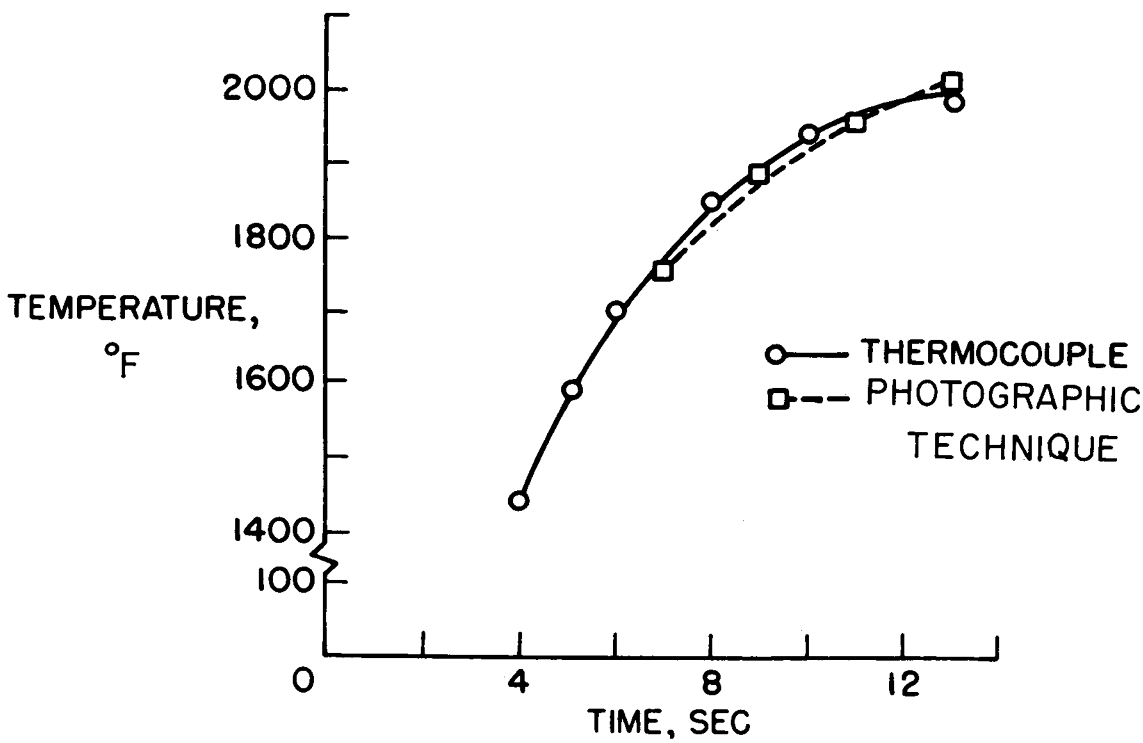

Figure 10.- Comparison of temperature as measured by thermocouple and photographic technique.

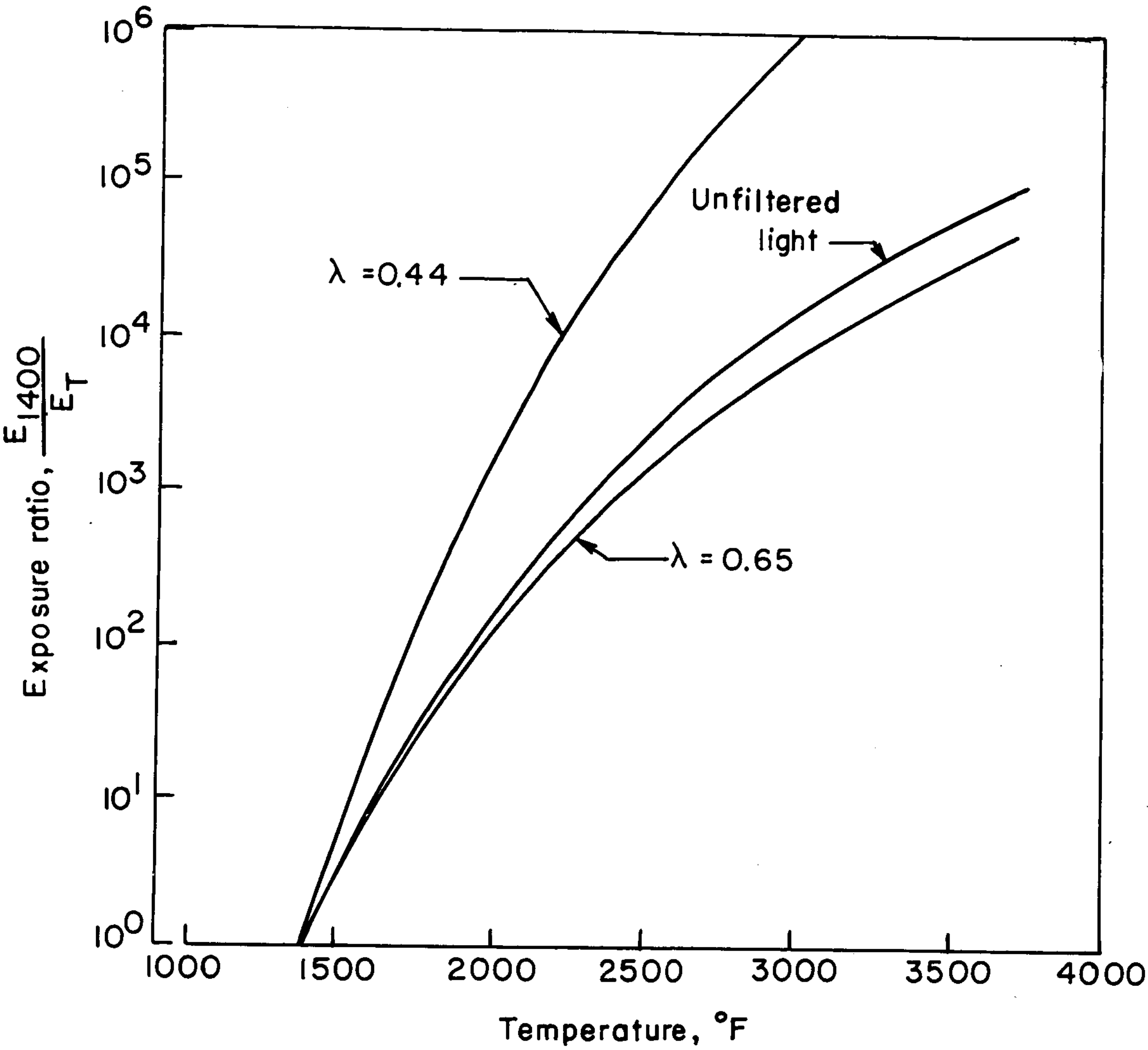

Figure 11.- Exposure-ratio curves for Kodak Tri-X Pan Film for filtered and unfiltered light.

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